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APPLICATION OF GENERATOR ANALYSIS METHODS

UNIVERSITY OF KENTUCKY
DEPARTMENT OF ELECTRICAL ENGINEERING
LEXINGTON KY 40506

APRIL 1977

TECHNICAL REPORT AFAPL–TR–77–31
FINAL REPORT FOR PERIOD JULY 1975 - SEPTEMBER 1976

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This technical report has been reviewed and is approved for publication.

Hugh L. Southall

HUGH L. SOUTHALL, Capt, USAF
Project Engineer

FOR THE COMMANDER

Richard L Verga

RICHARD L. VERGA
Technical Area Manager
Power Conditioning

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This study provides a theoretical model for simulating a wide variety of transient loading conditions for alternators. The model is represented as an equivalent circuit in a format compatible with the SCEPTRE computer program. SCEPTRE solves the resulting circuit equations for the transient response. Also addressed in this study is the inclusion of an effective saturation property into the SCEPTRE formulation resulting in a more realistic, and accurate nonlinear machine model.

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FOREWORD

This final report was submitted by the University of Kentucky, Lexington KY, 40506, under Contract F33615-76-C-2050. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Porject 3145, Task 32, and Work Unit 25 with Capt Hugh L. Southall, AFAPL/POD-1 as Project Engineer. The time period covered by the report is Jul 75 to Sep 76. Dr. R. J. Kuhler was technically responsible for the work performed.

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LIST OF ILLUSTRATIONS

SECTION I
INTRODUCTION

One of the primary considerations in the simulation of an isolated synchronous generator is that the system model be compatable with loading networks of many different varieties and yet that the introduction of changes in generator parameters or loading network be simply implemented. A further consideration is that machine parameters be easily identifiable in terms of the results of physical measurements. That these considerations are in conflict is recognizable by the fact that current standard machine practices give rise to measurements that normally identify parameters in direct-quadrature configuration, while the physical machine outputs are in the three phase configuration. For many loading network conditions, a spatial transformation such as Parks or Blondel transformation can be applied to the loads such that loads compatable with the direct-quadrature model are obtained. However, the introduction of various nonlinear load devices, such as rectifiers, dictates that both the machine representation and the load network representation be in a normal three phase formulation. An additional consideration suggesting compliance with three phase representation is the difficulty in inclusion of nonlinear effects, such as saturation, into the transformed model.

This study is an investigation of the required formulation of a synchronous machine time description such that properties previously discussed are incorporated into that formulation and such that the computation be time efficient. Also addressed in this study is the inclusion of an effective saturation property into the Sceptre formulation such that a more realistic, a more accurate nonlinear machine model is produced.

SECTION II
LINEARIZED MACHINE REPRESENTATION

The electrical schematic of a three phase machine and its circuit equivalent is shown in figure 1.1. The equations of motion for this representation are

$$\underline{v}(t) = \frac{d}{dt}\Big(L\, i(t) \Big) + R\, i(t) \qquad 1.1$$

$$\text{where } i(t) = \Big[\, i_a(t),\ i_b(t),\ i_c(t),\ i_f(t),\ i_d(t),\ i_q(t) \,\Big]$$

The order of this system with resistive loading is considered to be of sixth order. The only additional increase in system order necessary could be through inclusion of equivalent field driver circuitry, the possibility of which is included into the resulting simulation. The $i_d(t)$, $i_q(t)$ currents represent equivalent direct and quadrature damper currents which if flowing through their representative circuits would produce the effects of the machine damper structure or amortisseur windings and other circulating rotor currents. Under steady state operating conditions, the damper currents are zero. However, with the introduction of a load disturbance the resultant air gap flux field moves relative to the damper windings, resulting in a damping effect on the electrical transients introduced into the machine windings.

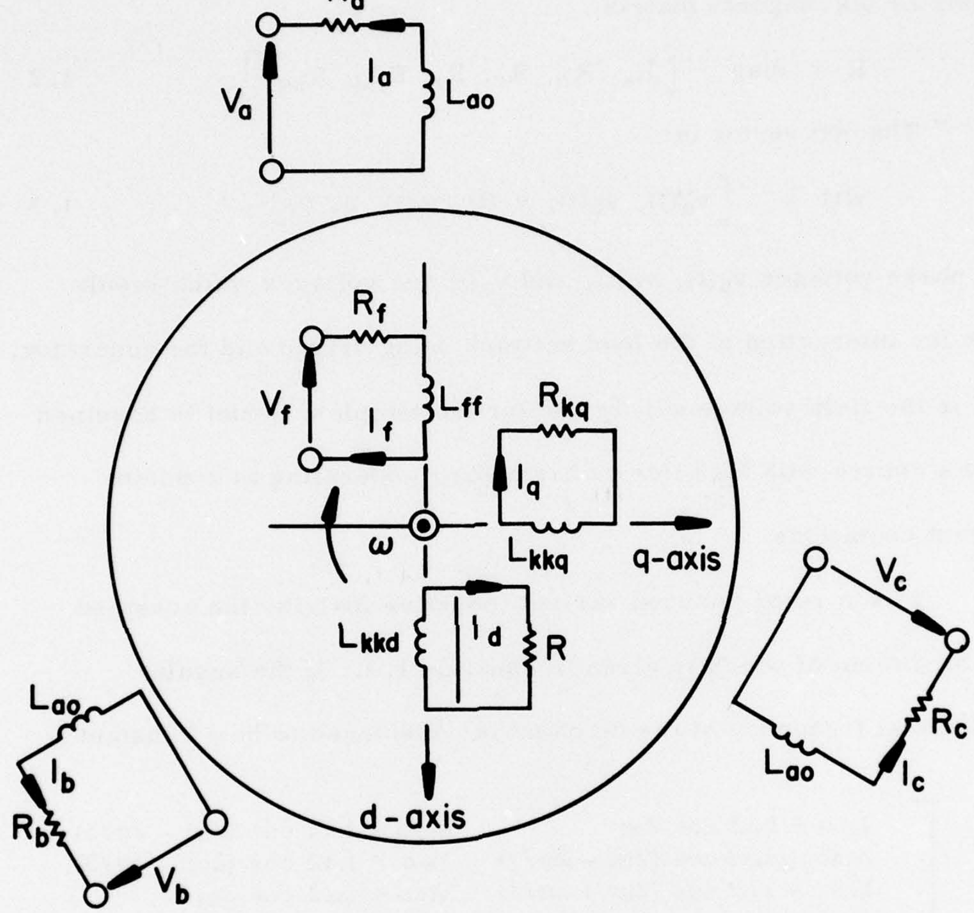

Figure 1.1 3ϕ Synchronous Machine Equivalent Circuit

The equivalent resistance in each circuit is represented by the six by six diagonal matrix,

$$R = \text{diag} \left[R_a,\ R_b,\ R_c,\ R_f,\ R_{kd},\ R_{kq} \right] \qquad 1.2$$

The v(t) vector is

$$v(t) = \left[v_a(t),\ v_b(t),\ v_c(t),\ v_f(t),\ 0,\ 0 \right] \qquad 1.3$$

The phase voltages $v_a(t)$, $v_b(t)$, and $v_c(t)$ are voltages which result from the interaction of the load network being driven and the generator. $v_f(t)$ is the field voltage supply and for the simplest model is assumed to be a source with high internal impedance operating at constant current conditions.

L is a rotor position varient inductive matrix, the accepted standard form of which is given in equation 1.4. If the angular mechanical frequency of the machine is considered to be a constant

$$L = \begin{array}{cc} \left[\begin{array}{cccccc} Lao + La2 \cos 2\omega t & Mso + La2 \cos(2\omega t - 2\pi/3) & Mso + La2 \cos(2\omega t + 2\pi/3) & Maf \cos \omega t & Maf \cos \omega t & -Maq \sin \omega t \\ Mso + La2 \cos(2\omega t - 2\pi/3) & Lao + La2 \cos(2\omega t - 2\pi/3) & Mso + La2 \cos 2\omega t & Maf \cos(\omega t - 2\pi/3) & Maf \cos(\omega t - 2\pi/3) & -Maq \sin(\omega t - 2\pi/3) \\ Mso + La2 \cos(2\omega t + 2\pi/3) & Mso + La2 \cos 2\omega t & Lao + La2 \cos(2\omega t - 2\pi/3) & Maf \cos(\omega t + 2\pi/3) & Maf \cos(\omega t + 2\pi/3) & -Maq \sin(\omega t + 2\pi/3) \\ Maf \cos \omega t & Maf \cos(\omega t - 2\pi/3) & Maf \cos(\omega t + 2\pi/3) & Lff & Mfkd & 0 \\ Maf \cos \omega t & Maf \cos(\omega t - 2\pi/3) & Maf \cos(\omega t + 2\pi/3) & Mfkd & Lkkd & 0 \\ -Maq \sin \omega t & -Maq \sin(\omega t - 2\pi/3) & -Maq \sin(\omega t + 2\pi/3) & 0 & 0 & Lkkq \end{array} \right] & \begin{array}{c} a \\ b \\ c \\ f \\ kd \\ kq \end{array} \end{array} \qquad 1.4$$

the machine equations can be rewritten in the form

$$L \frac{di(t)}{dt} + \dot{L}\, i(t) + R\, i(t) = v(t) \qquad 1.5$$

where

$$\dot{L} = \begin{array}{cccccc} a & b & c & f & d & q \\ \left| \begin{array}{c} -2\omega La2 \sin 2\omega t \\ -2\omega La2 \sin (2\omega t - 2\pi/3) \\ -2\omega La2 \sin (2\omega t + 2\pi/3) \\ -\omega Maf \sin \omega t \\ -\omega Maf \sin \omega t \\ -\omega Maq \cos \omega t \end{array} \right. & \begin{array}{c} -2\omega La2 \sin (2\omega t - 2\pi/3) \\ -2\omega La2 \sin (2\omega t + 2\pi/3) \\ -2\omega La2 \sin 2\omega t \\ -\omega Maf \sin (\omega t - 2\pi/3) \\ -\omega Maf \sin (\omega t - 2\pi/3) \\ -\omega Maq \cos (\omega t - 2\pi/3) \end{array} & \begin{array}{c} -2\omega La2 \sin (2\omega t + 2\pi/3) \\ -2\omega La2 \sin 2\omega t \\ -2\omega La2 \sin (2\omega t - 2\pi/3) \\ -\omega Maf \sin (\omega t + 2\pi/3) \\ -\omega Maf \sin (\omega t + 2\pi/3) \\ -\omega Maq \cos (\omega t + 2\pi/3) \end{array} & \begin{array}{c} -\omega Maf \sin \omega t \\ -\omega Maf \sin (\omega t - 2\pi/3) \\ -\omega Maf \sin (\omega t + 2\pi/3) \\ 0 \\ 0 \\ 0 \end{array} & \begin{array}{c} -\omega Maf \sin \omega t \\ -\omega Maf \sin (\omega t - 2\pi/3) \\ -\omega Maf \sin (\omega t + 2\pi/3) \\ 0 \\ 0 \\ 0 \end{array} & \left. \begin{array}{c} -\omega Maq \cos \omega t \\ -\omega Maq \cos (\omega t - 2\pi/3) \\ -\omega Maq \cos (\omega t + 2\pi/3) \\ 0 \\ 0 \\ 0 \end{array} \right| \end{array} \qquad 1.6$$

This assumption of constant frequency is only partially valid for most airborn auxiliary power units - its relaxation in the resulting simulation model does not produce traumatic changes in formulation. If the prime mover model is available the torque equation must be used along with the voltage equation because the rotor position becomes a nonperiodic function of time. However, in general, the synchronous generator has very little variation in frequency for severe load variations and the torque equations are not included in this model.

The resulting system of equations can be interpreted by examination of the first phase equation which takes the form

$$\left[L_{ao} + L_{a2} \cos 2\omega t\right] \frac{dia}{dt} + \left[M_{so} + L_{a2} \cos (2\omega t - 2\pi/3)\right] \frac{dib}{dt}$$

$$+ \left[M_{so} + L_{a2} \cos (2\omega t + 2\pi/3)\right] \frac{dic}{dt} + M_{af} \cos \omega t \quad \frac{dif}{dt}$$

$$+ M_{ad} \cos \omega t \frac{did}{dt} + M_{aq} \sin \omega t \frac{diq}{dt} - (2\omega L_{a2} \sin 2\omega t)\, i_a$$

$$- 2\omega L_{a2} \sin (2\omega t - 2\pi/3)\, i_b - 2\omega L_{a2} \sin (2\omega t + 2\pi/3)\, i_c$$

$$- M_{af}\, \omega \sin \omega t\, i_f - M_{ad}\, \omega \sin \omega t\, i_d - M_{aq}\, \omega \cos \omega t\, i_q$$

$$+ R_a\, i_a = v_a(t) \qquad 1.7$$

The equivalent circuit is thus seen to consist of self inductance with coupling mutuals plus a sequence of dependent sources which are functions of other currents inside the machine. In addition, there exists terms including the winding resistance and a time variable resistance in the phase loop. If all circuits are treated in the foregoing dependent voltage source manner the general circuit of figure 1.2 is produced. Furthermore, the form of most of the dependent sources is such that they are representable in Sceptre in a simple equation function. A Sceptre program for this portion of the generator model is listed in Appendix A.

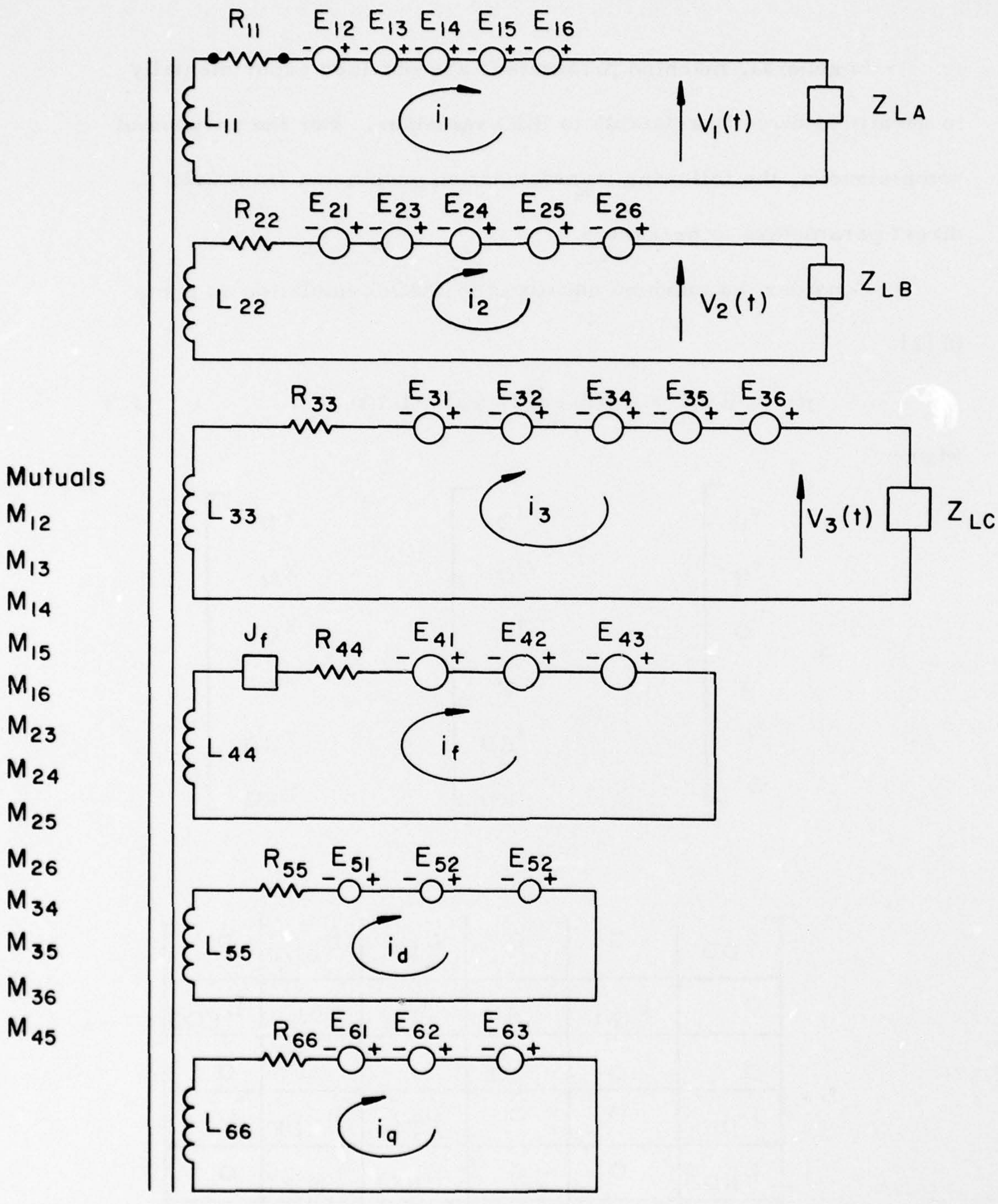

Figure 1.2 Sceptre Model Equivalent Circuit

SECTION III

MACHINE PARAMETERS IN DIRECT PHASE FORMULATION

In general, machine parameters are obtained experimentally in quantities directly relatable to DQO variables. For the purpose of completeness, the following transformation properties from DQO to direct parameters is presented.

Consider the machine equations in DQO formulation as given in [1].

$$v(t) = R\, i(t) + \Omega\, \chi(t) + \dot{\chi}(t), \quad \chi(t) = L\, i(t) \qquad 1.8$$

where

$$v = \begin{bmatrix} v_D \\ v_Q \\ v_O \\ v_F \\ O \\ O \end{bmatrix} \qquad i = \begin{bmatrix} -i_D \\ -i_Q \\ i_O \\ i_F \\ i_{KD} \\ i_{KQ} \end{bmatrix} \qquad \chi = \begin{bmatrix} \chi_D \\ \chi_Q \\ \chi_O \\ \chi_F \\ \chi_{KD} \\ \chi_{KQ} \end{bmatrix}$$

$$L = \begin{bmatrix} L_{DD} & O & O & L_{DF} & L_{KDD} & O \\ O & L_{QQ} & O & O & O & L_{KQQ} \\ O & O & L_O & O & O & O \\ L_{DF} & O & O & L_{FF} & L_{KDF} & O \\ L_{KDD} & O & O & L_{KDF} & L_{KDKD} & O \\ O & L_{KQQ} & O & O & O & L_{KQKQ} \end{bmatrix}$$

$$R = \mathrm{diag}\left[R_D, R_Q, R_O, R_F, R_{KD}, R_{KQ}\right]$$

and $\Omega_{ij} = 0$ for all i_{ij} except $\Omega_{12} = -\Omega_{21} = -\omega$. The direct phase variables are related to this set of DQO axis variables by the transformations

$$\underline{i}_{abc} = B^{-1}\,\underline{i}_{DQO} \qquad v_{abc} = B^{-1}\,v_{DQO} \tag{1.9}$$

where a suitable B^{-1} is given by

$$B^{-1} = \sqrt{2/3}\begin{bmatrix} \cos\omega t & -\sin\omega t & 1/\sqrt{2} \\ \cos(\omega t - 2\pi/3) & -\sin\omega t - 2\pi/3 & 1/\sqrt{2} \\ \cos(\omega t + 2\pi/3) & -\sin(\omega t + 2\pi/3) & 1/\sqrt{2} \end{bmatrix} \tag{1.10}$$

Transforming equation 1.8 to direct phase quantities via 1.9 gives

$$B\,v_{abc} = R\,B\,i_{abc} + \Omega\,L\,B\,i_{abc} + L\,\dot{B}\,i_{abc} + L\,B\,\frac{di_{abc}}{dt} \tag{1.11}$$

or

$$v_{abc} = B^{-1}\,R\,B\,i_{abc} + \left[B^{-1}\,\Omega\,L\,B + B^{-1}\,L\,\dot{B}\right]i_{abc} + B^{-1}\,L\,B\,\frac{di_{abc}}{dt} \tag{1.12}$$

Comparison of equations 1.12 and 1.5 indicate that

$$L_{abc} = B^{-1}\,L_{DQO}\,B$$

$$R_{abc} = B^{-1}\,R_{DQO}\,B$$

As all possible resistance measurements are normally made in direct phase form, no transformation is necessary. However, inductance calculation from synchronous and transient reactances is normally in terms of L_{DQO} and matrix entries of equation 1.4 are related to L_{DQO} entries as follows:

$$L_{ao} = 1/3 \left[L_{DD} + L_{QQ} + L_O \right]$$

$$L_{a2} = 1/3 \left[L_{DD} + L_{QQ} \right]$$

$$M_{so} = 1/6 \left[L_{DD} + L_{QQ} \right]$$

$$L_{kkd} = L_{KDKD}$$

$$L_{kkq} = L_{KQKQ}$$

$$L_{ff} = L_{FF}$$

$$M_{ad} = M_{af} = L_{FD}$$

$$M_{aq} = L_{KQQ}$$

$$M_{fkd} = L_{KDF}$$

Of course, the per unit denormalization must first be accounted for to acquire direct phase parameters which represent the physical machine and reproduce the proper level voltage and current variables.

SECTION IV
LINEAR MACHINE SIMULATION

The parameter set in [1] was used to simulate a machine in the Sceptre format. The parameters were unnormalized to give the physical phase voltages and currents under normal operating conditions. The model and parameters of Program in Appendix A were run in various load and switched load conditions. Figures 1.3 and 1.4 show the current and voltage waveforms on the A phase as the open circuit machine has a .5Ω load placed on the A phase. Figures 1.5 and 1.6 show the result on the A phase variable as the machine has a 3 phase line to neutral .5Ω load applied on phases B and C. These

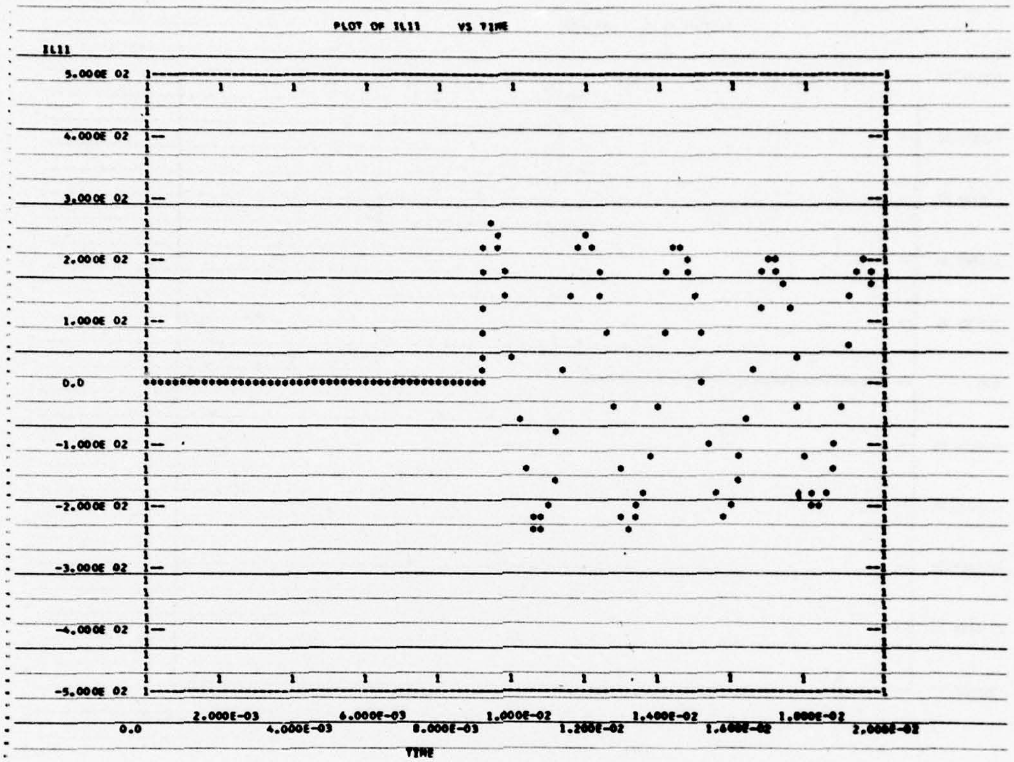

Figure 1.3 A Phase Current, Line-Neutral Short (.5Ω) on A Phase

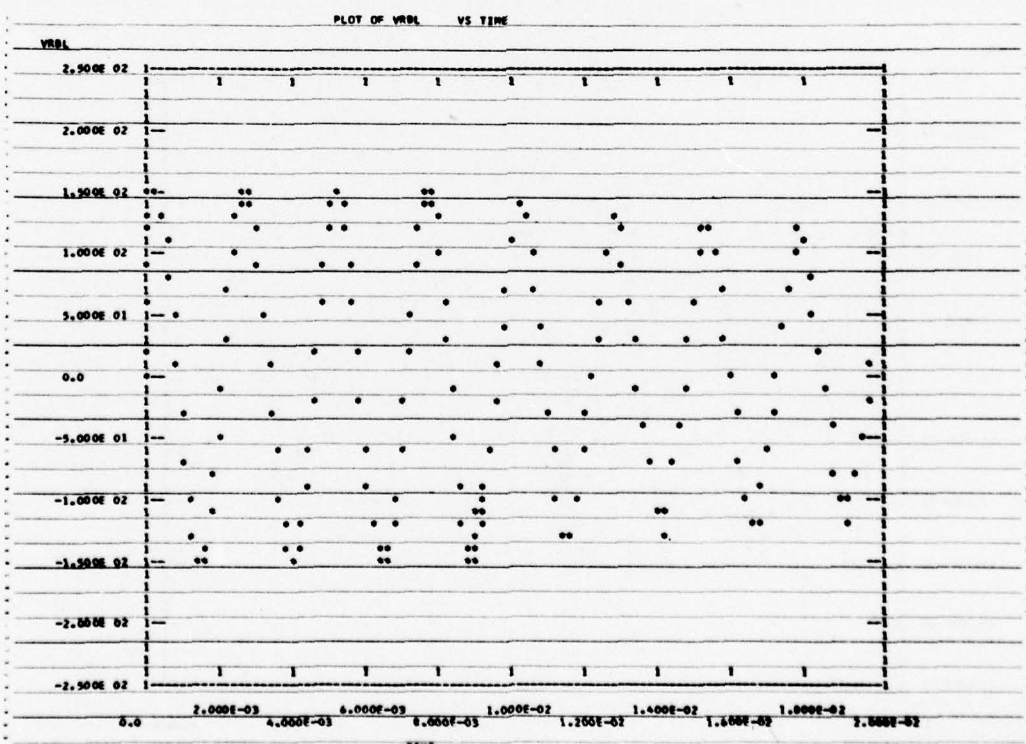

Figure 1.4 B Phase Voltage, Line-Neutral Short (.5Ω) on A Phase

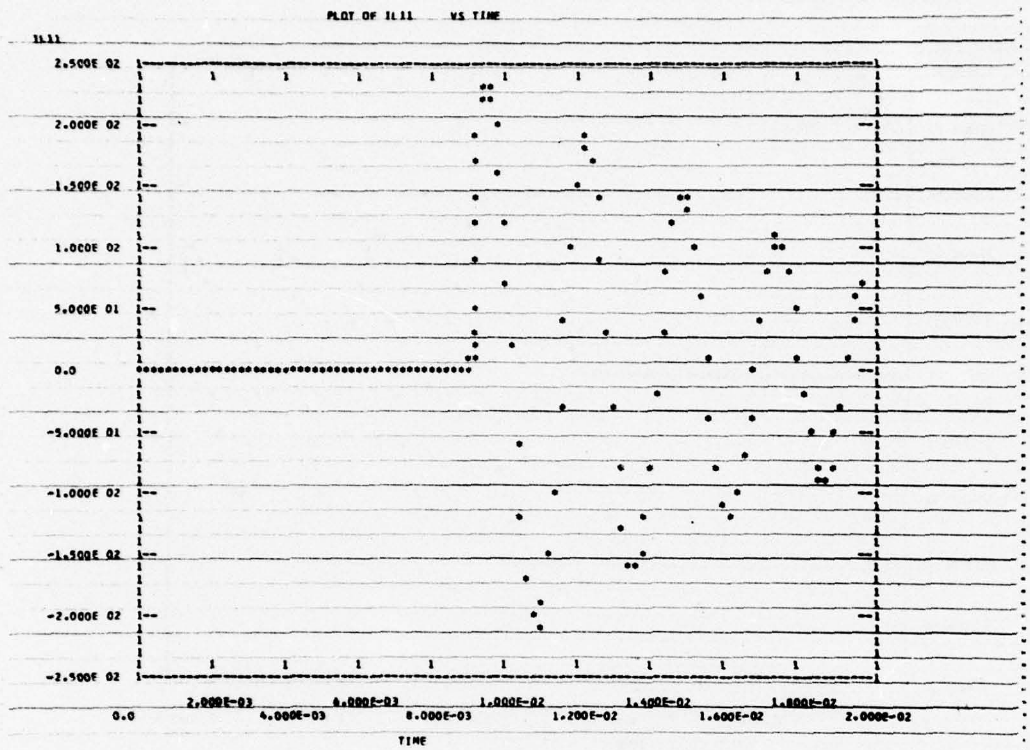

Figure 1.5 A Phase Current - 2ϕ Line to Neutral Short (.5Ω)

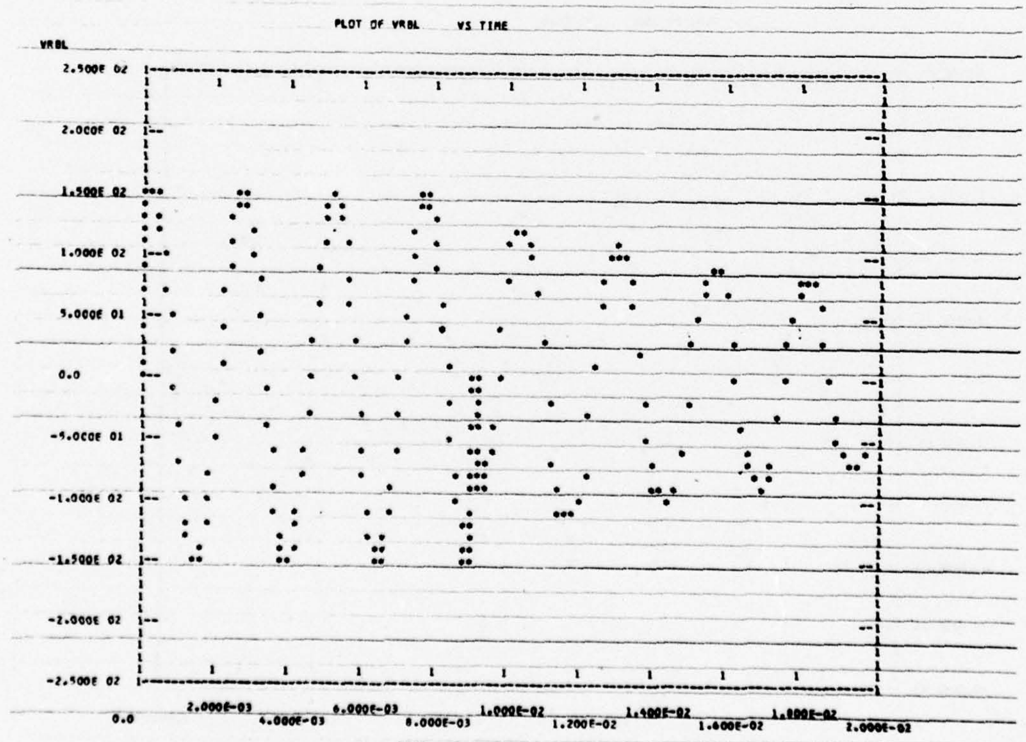

Figure 1.6 B Phase Voltage - 2ϕ Line to Neutral Short (.5Ω)

computational values can be contrasted with the experimental results obtained from lab tests on a similar 60 KVA machine at WPAFB. (Same model, but different machine.) These results are shown in figure 1.7. The open circuit machine has a 2 phase line to neutral load of approximately $.5\Omega$ applied on phases B and C. The final values which the machine voltage and currents approach are approximately equal for model and machine, however, the time constant in arriving at the final values is slightly different.

This indicates that field coupling and resistive values are approximately correct, however, damper circuit values are such that their action is too dominant on the machine response.

It is instructive to compare the simulation time for this machine in the Sceptre format with results utilizing different numerical techniques for the time solution of differential equations. For problems involving application of transient load networks, the most severe accuracy requirements occur immediately following the transient, thus figure 1.4 represents a typical loading situation. The total CPU time on an IBM 370 Computer for problem solution excluding Sceptre set-up time for this example was .22 minutes or 13 seconds. Typical open circuit to short circuit computation time including start up transient from zero initial conditions is of the order of 2 to 4 seconds/cycle for this linear model.

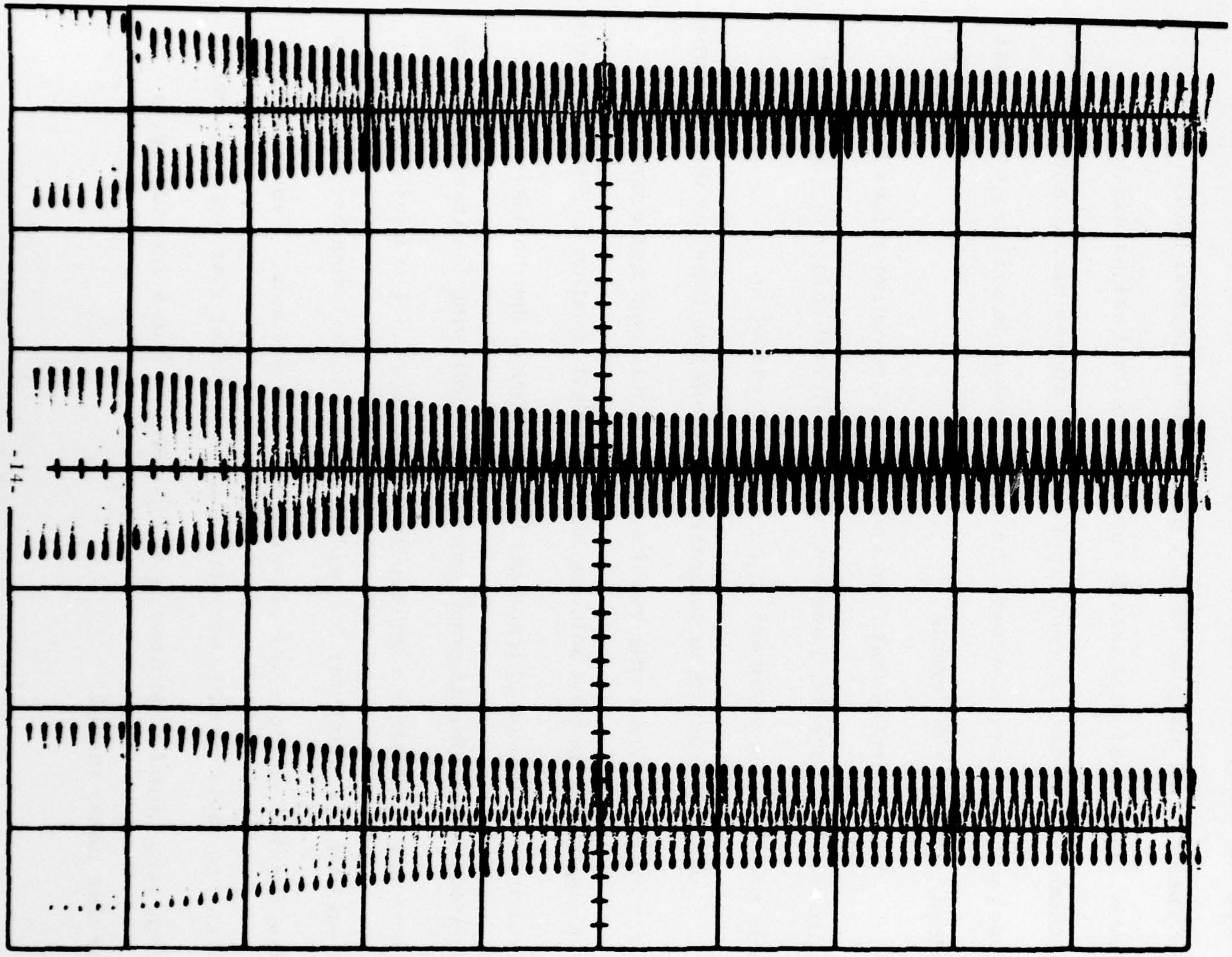

Figure 1.7 60KVA Machine Voltage Waveforms - 2ϕ Line to Neutral Short (approx. 1/2Ω)

SECTION V

SIMULATION OF GENERATOR SATURATION CONDITIONS

The terms in the machine equation 1.1 involving the time derivative of the product $L\underline{i}(t)$ in general cannot be separated into the form of equation 1.5. This condition arises in saturation because the inductance elements of the L matrix are functions of both time and current. However, it is usual practice to invoke a separation principle in the analysis of a saturated synchronous generator.

This separation principle [2] is based upon the operation of considering the derivative $\frac{d}{dt}\left[L(\underline{i}, t)\, \underline{i}(t)\right]$ as the sum $L(i, t) \frac{d}{dt} i(t) + \dot{L}(i, t)\, i(t)$. Under this assumption it can be seen that a partial derivative of the form $\frac{\partial L}{\partial i} \frac{\partial i(t)}{\partial t}$ has been excluded. The justification of this saturation principle in the past has been based upon agreement between predicted and measured results.

The approach utilized in this simulation is to calculate an equivalent flux with a linear combination of the currents of the windings. The combination of currents for flux calculations is taken to be

$$\chi_{SAT} = L_A^T\, \underline{i}(t) \qquad 1.13$$

where

$$L_A = \begin{bmatrix} M_{af} \cos \omega t \\ M_{af} \cos (\omega t - 2\pi/3) \\ M_{af} \cos (\omega t + 2\pi/3) \\ L_{ff} \\ M_{FKD} \end{bmatrix} \qquad i(t) = \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \\ i_d \end{bmatrix}$$

It is seen that the flux calculation is such that the linear combination of currents produces a rotating magnetic field colinear with the magnetic field produced by the field winding. The inductance values are modified as a function of the calculated flux and a saturation curve for the machine.

A saturation curve for a 60 KVA auxiliary power unit is shown in figure 1.8. This curve is obtained through plotting open circuit phase voltage measurements versus field current when rotating at synchronous speed. The zero power factor curve will be used in this model because of the absence of definable power factor conditions under transient conditions. If the saturation curve is inverted and normalized such than an equivalent coupling between field and phase is computed for all values along the saturation curve, the result shown in figure 1.9 is obtained. Thus the inclusion of the saturation condition is equivalent to modifying the machine inductances by a ratio determined by the calculated flux as given in equation 1.3 and figure 1.9.

The mechanics of including this effect into the machine model is greatly simplified under the dependent source equation format utilized in the preceding model. A table lookup with the saturation curves versus calculated flux is used to determine the reduction factor for the inductance values. A circuit containing dummy dependent sources which calculate the flux level and linkage for the equivalent physical orientation of the phases and field windings is introduced. The source value for the physical alignment of each coil with the resulting field is used as the independent variable in the table lookup.

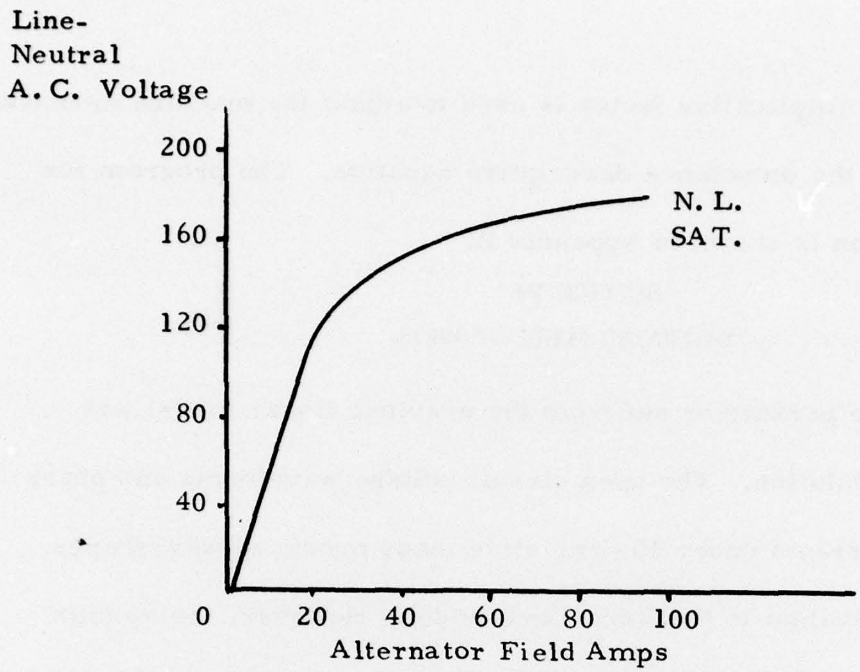

Figure 1.8 60KVA Machine Saturation Curves

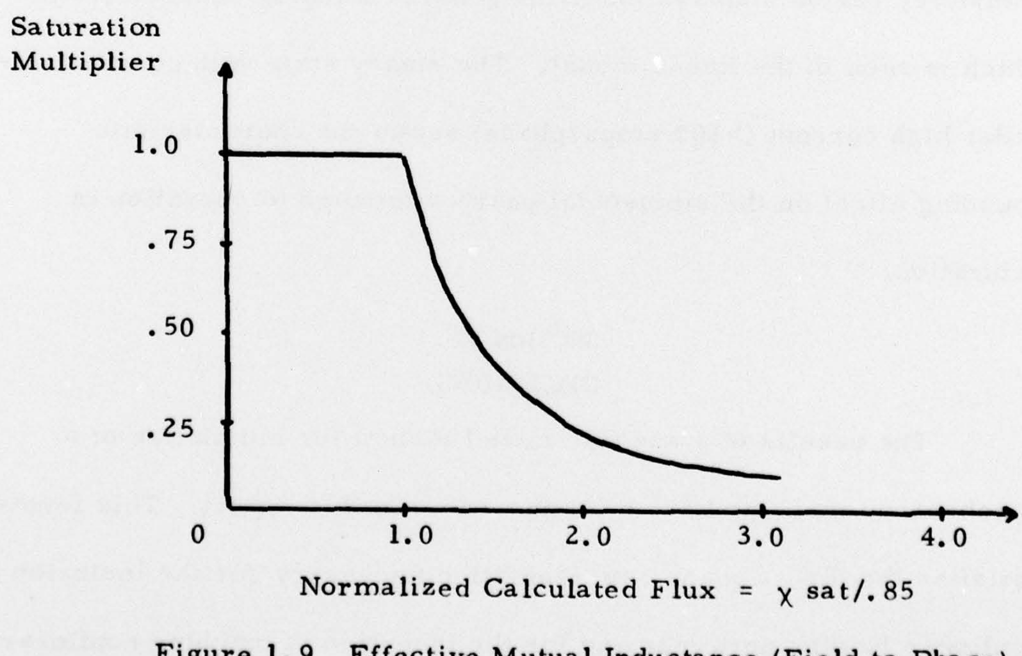

Figure 1.9 Effective Mutual Inductance (Field to Phase) Multiplier for Linear and Saturation Regions

The resulting multiplicative factor is used to adjust the machine inductive parameters via the inductance descriptive equation. The program for this configuration is shown in Appendix B.

SECTION VI
SATURATED MODEL RESULTS

The base parameter set from the previous linear model was used in this simulation. The open circuit voltage waveforms and phase voltages and currents under 10Ω resistive loads produced waveshapes which were equivalent to the linearized model. However, the results under transient loading conditions produced waveshapes with high 3rd harmonic content. A typical result is shown in figures 1.10 and 1.11. In this case the load on A phase is switched from 10Ω to .01Ω. The transitory region displays the same general damping characteristic which is seen in the linear model. The steady state voltage waveform under high current (>100 amps/phase) shows the characteristic rounding effect on the simusoidal peaks attributed to operation in saturation.

SECTION VI
CONCLUSIONS

The results of a specific model format for simulation of a synchronous machine have been presented in this report. This format satisfies the direct phase representation necessary for the inclusion of nonlinear loading networks and for the insertion of machine nonlinearities. A method of insertion of the saturation effect into the machine

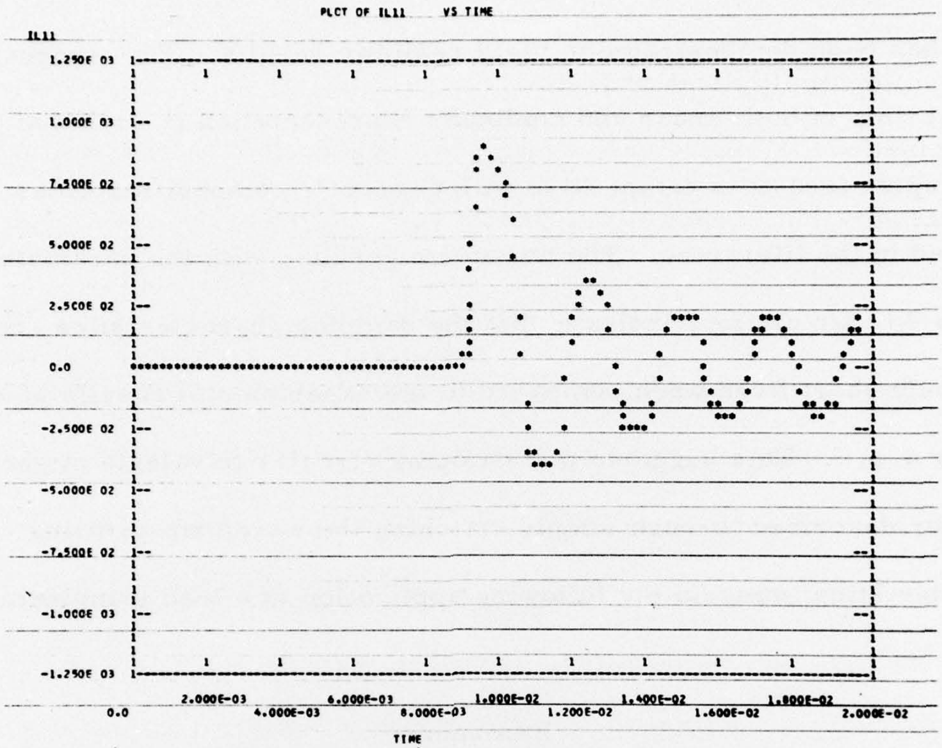

Figure 1.10 Saturation Model - A Phase Current - Line to Neutral Short (.01Ω) on A Phase

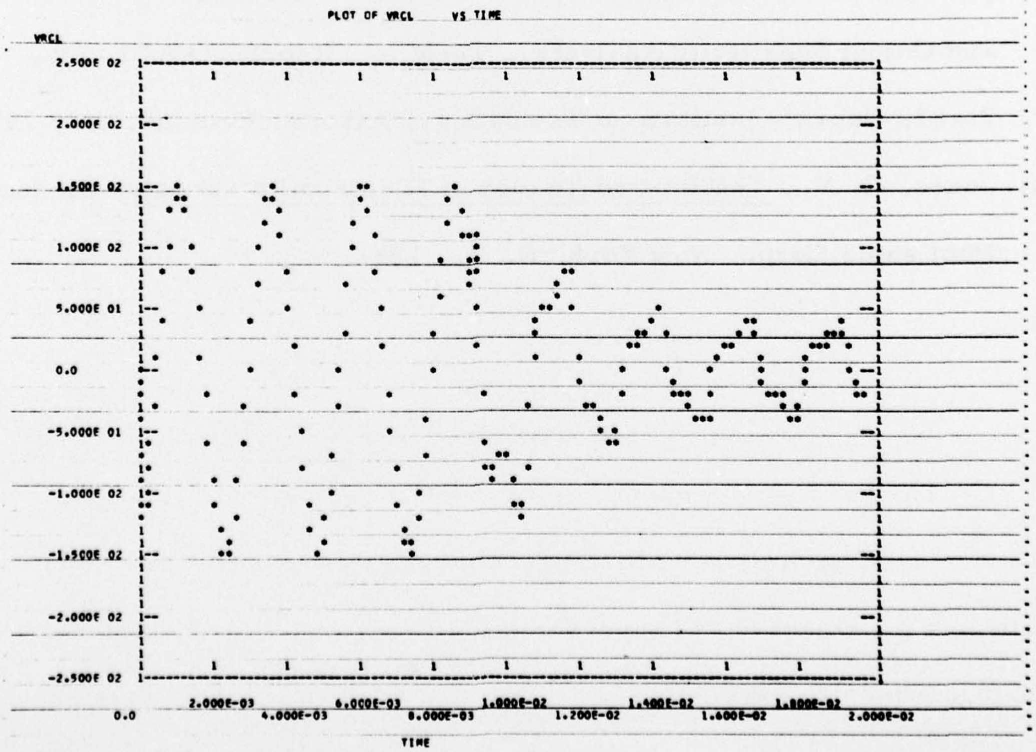

Figure 1.11 Saturation Model - C Phase Voltage - Line to Neutral Short (.01Ω) on A Phase

model has been demonstrated to yield realistic results. The computational time of both linear and nonlinear representation is such that this Sceptre format is competitive with per/cycle computation times reported in the literature. The waveform results, with the parameters used in this simulation, indicate that the damping characteristics are extremely short lived when compared to the experimental results of a similar a.p.u. This suggests that damping circuit equivalents might be better described through simply matching the waveform damping characteristics immediately following application of a load transient.

References

[1] "Alternator Modeling Part 1, Simulation, Parameter Estimation and Output Sensitivity Analysis", Technical Report AFAPL-TR-75-87, Georgia Institute of Technology, Atlanta, Georgia, July 1975.

[2] Jones, C. V., The Unified Theory of Electrical Machines, Plenum Publishing Corp., New York, N. Y., 1967.

APPENDIX A

LINEAR MACHINE SCEPTRE MODEL PROGRAM

```
SCEPTRE SYSTEM INPUT --  4/72 VERSION -- S/360 -- OS RELEASE 20.1


CIRCUIT DESCRIPTION
ELEMENTS
J1,44-0=10.0
RAL,71-0=1000.
RBL,72-0=T1
RCL,73-0=T1
RA,1-11=PRP
RB,2-12=PRP
RC,3-13=PRP
R33,13-23= EQUATION 3 (-1.,PLA2,-2.0944)
R22,12-22= EQUATION 3 (-1.,PLA2,2.0944)
R11,11-21= EQUATION 3 (-1.,PLA2,0.0)
RF,4-14=PRF
RD,5-15=PRD
RQ,6-16=PRQ
E12,21-31=EQUATION 3 (IL22,PLA2,-2.0944)
E13,31-41=EQUATION 3 (IL33,PLA2,2.0944)
E14,41-51=EQUATION 4 (IL44,PMAF,0.0)
E15,51-61= EQUATION 4 (IL55,PMAD,0.0)
E16,61-71= EQUATION 5 (IL66,PMAQ,0.0)
E21,22-32= EQUATION 3 (IL11,PLA2,-2.0944)
E23,32-42= EQUATION 3 (IL33,PLA2,0.0)
E24,42-52= EQUATION 4 (IL44,PMAF,-2.0944)
E25,52-62= EQUATION 4 (IL55,PMAD,-2.0944)
E26,62-72= EQUATION 5 (IL66,PMAQ,-2.0944)
E31,23-33= EQUATION 3 (IL11,PLA2,2.0944)
E32,33-43= EQUATION 3 (IL22,PLA2,0.0)
E34,43-53= EQUATION 4 (IL44,PMAF,2.0944)
E35,53-63= EQUATION 4 (IL55,PMAD,2.0944)
E36,63-73= EQUATION 5 (IL66,PMAQ,2.0944)
E41,14-24= EQUATION 4 (IL11,PMAF,0.0)
E51,15-25= EQUATION 4 (IL11,PMAD,0.0)
E42,24-34= EQUATION 4 (IL22,PMAF,-2.0944)
E52,25-35= EQUATION 4 (IL22,PMAD,-2.0944)
E53,35-0 = EQUATION 4 (IL33,PMAD,2.0944)
E43,34-44= EQUATION 4 (IL33,PMAF,2.0944)
E61,16-26= EQUATION 5 (IL11,PMAQ,0.0)
E62,26-36= EQUATION 5 (IL22,PMAQ,-2.0944)
E63,36-0 = EQUATION 5 (IL33,PMAQ,2.0944)
L11,0-1= EQUATION 1 (PLA0,PLA2,0.0)
L22,0-2= EQUATION 1 (PLA0,PLA2,2.0944)
L33,0-3= EQUATION 1 (PLA0,PLA2,-2.0944)
L44,0-4=PLFF
L55,0-5=PLKKD
L66,0-6=PLKKQ
M45,L44-L55=PMFKD
M12,L11-L22= EQUATION 1 (PMSO,PLA2,-2.0944)
M13,L11-L33= EQUATION 1 (PMSO,PLA2,2.0944)
M15,L11-L55= EQUATION 9 ( 1.0,PMAD,0.0)
M14,L11-L44= EQUATION 9 ( 1.0,PMAF,0.0)
M23,L22-L33= EQUATION 1 (PMSO,PLA2,0.0)
M24,L22-L44= EQUATION 9 ( 1.0,PMAF,-2.0944)
M25,L22-L55= EQUATION 9 ( 1.0,PMAD,-2.0944)
M34,L33-L44= EQUATION 9  ( 1.0,PMAF,2.0944)
M35,L33-L55= EQUATION 9  ( 1.0,PMAD,2.0944)
M16,L11-L66= EQUATION 8 (-1.0,PMAQ,0.0)
M26,L22-L66= EQUATION 8 (-1.0,PMAQ,-2.0944)
M36,L33-L66= EQUATION 8 (-1.0,PMAQ,+2.0944)
```

```
DEFINED PARAMETERS
PRQ=.0778
PRD=.0778
PRP=.0457
PRF=.0905
PLA0=.000442
PLA2=.00009
PLFF=.085
PLKKD=.00078
PLKKQ=.000515
PMS0=-.000221
PMFKD=.0078
PMAF=-.00608
PMAQ=-.0004
PMAD=-.00060
PW=2512.
FUNCTIONS
EQUATION 1 (A,B,C) = (A+B*DCOS(2.*PW*TIME+C))
EQUATION 3 (A,B,C) = (2.*A*B*PW*DSIN(2.*PW*TIME+C))
EQUATION 4 (A,B,C) = (A*B*PW*DSIN(PW*TIME+C))
EQUATION 5 (A,B,C) = (A*B*PW*DCOS(PW*TIME+C))
EQUATION 7 (A,B,C) = ( 2.*A*B*DSIN(2.*PW*TIME+C))
EQUATION 8 (A,B,C) = ( A*B*DSIN(PW*TIME+C))
EQUATION 9 (A,B,C) = ( A*B*DCOS(PW*TIME+C))
T1
0.0,1000.,0.009,1000.,.0091,.5,.02,.5
OUTPUTS
VRAL,VRBL,IL11,IL66,PLOT
RUN CONTROLS
INTEGRATION ROUTINE=IMPLICIT
STOP TIME =0.02
END
```

APPENDIX B

SCEPTRE SATURATION MODEL PROGRAM

```
SCEPTRE SYSTEM INPUT --  4/72 VERSION -- S/360 -- OS RELEASE 20.1

CIRCUIT DESCRIPTION
ELEMENTS
ES1,0-A=FSAT(IL11,IL22,IL33,IL44,IL55,0.0,TIME)
ES2,B-C=FSAT(IL11,IL22,IL33,IL44,IL55,-2.0944,TIME)
ES3,A-B=FSAT(IL11,IL22,IL33,IL44,IL55,+2.0944,TIME)
ES4,C-D=FSAT(IL11,IL22,IL33,IL44,IL55,1.0,TIME)
RDEL,D-0=1000.
J1,44-0=10.0
RAL,71-0=T2
RBL,72-0=10.
RCL,73-0=10.
RA,1-11=PRP
RB,2-12=PRP
RC,3-13=PRP
R11,11-21= EQUATION 3 (-1.,PLA2,0.0,TABLE 1 (ES1))
R22,12-22= EQUATION 3 (-1.,PLA2,2.0944,TABLE 1 (ES2))
R33,13-23= EQUATION 3 (-1.,PLA2,-2.0944,TABLE 1 (ES3))
RF,4-14=PRF
RD,5-15=PRD
RQ,6-16=PRQ
E12,21-31=EQUATION 3 (IL22,PLA2,-2.0944,TABLE 1 (ES1))
E13,31-41=EQUATION 3 (IL33,PLA2,2.0944,TABLE 1 (ES1))
E14,41-51=EQUATION 4 (IL44,PMAF,0.0,TABLE 1 (ES1))
E15,51-61= EQUATION 4 (IL55,PMAD,0.0,TABLE 1 (ES1))
E16,61-71= EQUATION 5 (IL66,PMAQ,0.0,TABLE 1 (ES1))
E21,22-32= EQUATION 3 (IL11,PLA2,-2.0944,TABLE 1 (ES2))
E23,32-42= EQUATION 3 (IL33,PLA2,0.0,TABLE 1 (ES2))
E24,42-52= EQUATION 4 (IL44,PMAF,-2.0944,TABLE 1 (ES2))
E25,52-62= EQUATION 4 (IL55,PMAD,-2.0944,TABLE 1 (ES2))
E31,23-33= EQUATION 3 (IL11,PLA2,2.0944,TABLE 1 (ES3))
E26,62-72= EQUATION 5 (IL66,PMAQ,-2.0944,TABLE 1 (ES2))
E32,33-43= EQUATION 3 (IL22,PLA2,0.0,TABLE 1 (ES3))
E34,43-53= EQUATION 4 (IL44,PMAF,2.0944,TABLE 1 (ES3))
E35,53-63= EQUATION 4 (IL55,PMAD,2.0944,TABLE 1 (ES3))
E36,63-73= EQUATION 5 (IL66,PMAQ,2.0944,TABLE 1 (ES3))
E41,14-24= EQUATION 4 (IL11,PMAF,0.0,TABLE 1 (ES4))
E42,24-34= EQUATION 4 (IL22,PMAF,-2.0944,TABLE 1 (ES4))
E43,34-44= EQUATION 4 (IL33,PMAF,2.0944,TABLE 1 (ES4))
E63,36-0 = EQUATION 5 (IL33,PMAQ,2.0944,TABLE 1 (ES3))
E62,26-36= EQUATION 5 (IL22,PMAQ,-2.0944,TABLE 1 (ES2))
E61,16-26= EQUATION 5 (IL11,PMAQ,0.0,TABLE 1 (ES1))
E53,35-0 = EQUATION 4 (IL33,PMAD,2.0944,TABLE 1 (ES4))
E52,25-35= EQUATION 4 (IL22,PMAD,-2.0944,TABLE 1 (ES4))
E51,15-25= EQUATION 4 (IL11,PMAD,0.0,TABLE 1 (ES4))
L44,0-4= EQUATION 6 (PLFF,TABLE 1 (ES4))
L55,0-5= EQUATION 6 (PLKKD,TABLE 1 (ES4))
L66,0-6=PLKKQ
M45,L44-L55= EQUATION 6 (PMFKD,TABLE 1 (ES4))
L33,0-3= EQUATION 1 (PLA0,PLA2,-2.0944,TABLE 1 (ES3))
L22,0-2= EQUATION 1 (PLA0,PLA2,2.0944,TABLE 1 (ES2))
L11,0-1= EQUATION 1 (PLA0,PLA2,0.0,TABLE 1 (ES1))
M16,L11-L66= EQUATION 8 (-1.0,PMAQ,0.0,TABLE 1 (ES1))
M15,L11-L55= EQUATION 9 ( 1.0,PMAD,0.0,TABLE 1 (ES4))
M14,L11-L44= EQUATION 9 ( 1.0,PMAF,0.0,TABLE 1 (ES4))
M13,L11-L33= EQUATION 1 (PMS0,PLA2,2.0944,TABLE 1 (ES1))
M23,L22-L33= EQUATION 1 (PMS0,PLA2,0.0,TABLE 1 (ES2))
```

```
M25,L22-L55= EQUATION 9 ( 1.0,PMAD,-2.0944,TABLE 1 (FS4))
M26,L22-L66= EQUATION 8 (-1.0,PMAQ,-2.0944,TABLE 1 (FS2))
M35,L33-L55= EQUATION 9  ( 1.0,PMAD,2.0944,TABLE 1 (FS4))
M36,L33-L66= EQUATION 8 (-1.0,PMAQ,+2.0944,TABLE 1 (FS3))
M12,L11-L22= EQUATION 1 (PMSO,PLA2,-2.0944,TABLE 1 (FS1))
M24,L22-L44= EQUATION 9 ( 1.0,PMAF,-2.0944,TABLE 1 (FS4))
M34,L33-L44= EQUATION 9  ( 1.0,PMAF,2.0944,TABLE 1 (FS4))
DEFINED PARAMETERS
PRQ=.0778
PRD=.0778
PRP=.0457
PRF=.0905
PLA0=.000442
PLA2=.00009
PLFF=.085
PLKKD=.00078
PLKKQ=.000515
PMSO=-.000221
PMFKD=.0078
PMAF=-.00608
PMAQ=-.0004
PMAD=-.00060
PW=2512.
FUNCTIONS
EQUATION 9 (A,B,C,D) = (( A*B*DCOS(PW*TIME+C))*D)
EQUATION 8 (A,B,C,D) = (( A*B*DSIN(PW*TIME+C))*D)
EQUATION 7 (A,B,C,D) = (( 2.*A*B*DSIN(2.*PW*TIME+C))*D)
EQUATION 6 (A,B) = (A*B)
EQUATION 5 (A,B,C,D) = ((A*B*PW*DCOS(PW*TIME+C))*D)
EQUATION 4 (A,B,C,D) = ((A*B*PW*DSIN(PW*TIME+C))*D)
EQUATION 3 (A,B,C,D) = ((2.*A*B*PW*DSIN(2.*PW*TIME+C))*D)
EQUATION 1 (A,B,C,D) = ((A+B*DCOS(2.*PW*TIME+C))*D)
TABLE 1
0.0,1.0,1.0,1.0,1.5,.8,2.0,.7,2.5,.54,3.0,.44,4.0,.36,5.0,.3
T2
0.0,10.0,0.009,10.0,0.0091,0.01,0.02,0.01
OUTPUTS
IL11,VRBL,VRCL,IL55,IL66,PLOT
RUN CONTROLS
INTEGRATION ROUTINE=IMPLICIT
STOP TIME =0.03
MINIMUM STEP SIZE = 1.0E-11
END
INDICES FOR STATE VARIABLE DERIVATIVE NAMES

          1     DL55
          2     DL66
          3     DL33
          4     DL22
          5     DL11
```

```
 DOUBLE PRECISION FUNCTION FSAT(AL,BL,CL,DL,EL,FL,TIME)
 IMPLICIT REAL*8(A-J,L-M,O-Z),INTEGER*4(K,N)
 PW=2512.
 PMAF=-.00608
 PLFF=.085
 PMFKD=.0078
 FLUX=PMAF*AL*DCOS(PW*TIME)+PMAF*BL*DCOS(PW*TIME-2.0944)+PMAF*CL*
* DCOS(PW*TIME+2.0944)+PLFF*DL+PMFKD*EL
 FSAT=DABS(DCOS(PW*TIME-FL)*FLUX)
 IF (FL.EQ.1.0) FSAT=DABS(FLUX)
 RETURN
 END
```


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